Guidelines for Applying IEC Standards to Electrical Distribution Equipment

Part 4

IEC equipment standards

power transformers

introduction

This part of the tutorial examines the use of some IEC standards related to power transformers. Power transformers from 500kVA distribution transformers to 150MVA main step-down transformers can be found in industrial plants. Since power transformers are major pieces of equipment in any plant it is not surprising that there has been so much work done to standardize their performance characteristics and to help engineers correctly specify them. Due to their importance it is vital to make sure that they meet the requirements of the application. The failure of a main transformer can result in millions of dollars in lost production in addition to the cost of a new transformer. Points which can and often lead to confusion are explained and demonstrated by examples based on actual cases.

applicable IEC standards

The main IEC standards for oil-immersed and dry-type power transformers are listed below. Several are grouped together as parts of IEC60076 whereas the others have different numbers. It is evident from this list that care must be taken to have all relevant documents including amendments. The latest standard was issued in 1997. There are more on the way. The IEC web site should be consulted in case of any doubts about applicable standards.

☐ IEC60076 power transformers

☐ IEC60076-1 (1993) power transformers: general (replaces IEC60076-4)

☐ IEC60076-2 (1993) power transformers: temperature rise

☐ IEC60076-3 (1980) power transformers: insulation levels and dielectric tests

Amendment 1 (1981)

☐ IEC60076-3-1 (1987) power transformers: insulation levels and dielectric tests, external clearances

in air

☐ IEC60076-5 (1976) power transformers: ability to withstand short circuit

Amendment 1 (1979)

Amendment 2 (1994)

☐ IEC60076-8 (1997) power transformers: application guide (replaces IEC60606)

☐ IEC60214 (1989) on-load tap changers

☐ IEC60354 (1991) loading guide for oil-immersed power transformers

☐ IEC60542 (1976) application guide for on-load tap changers

Amendment 1 (1988)

☐ IEC60616 (1978) terminal & tapping marking for power transformers

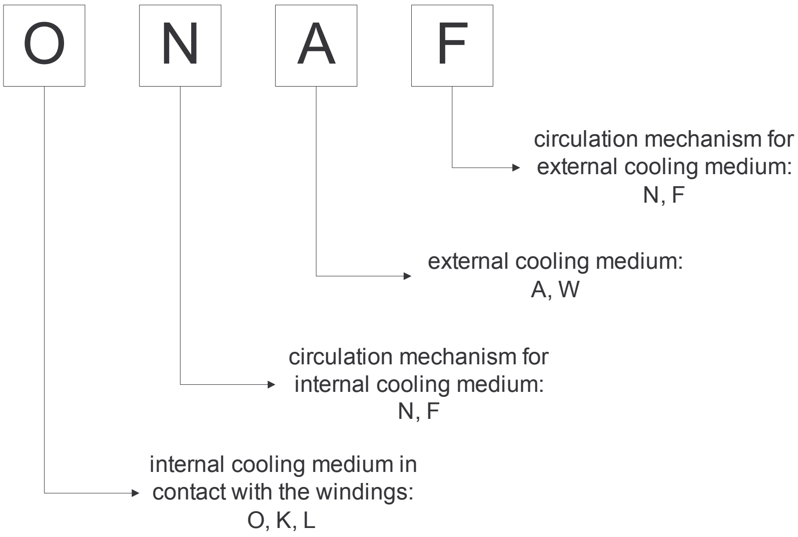
In addition there are some standards which apply specifically to dry-type transformers. These standards often refer to clauses in the standards listed above.

☐ IEC60726 (1982) dry-type power transformers

Amendment 1 (1986)

☐IEC60905 (1987) loading guide for dry-type power transformers

Transformer cooling method designation


O
N
A
F
circulation mechanism for external cooling medium: N, F
external cooling medium: A, W
circulation mechanism for internal cooling medium: N, F
internal cooling medium in contact with the windings: O, K, L

cooling method identification

As an introduction to the sections discussing the definition of the rated apparent power, the different cooling methods as defined in clause 3 of *IEC60076-2 temperature rise* are reviewed. For oil-immersed power transformers the cooling method is defined by the following letters.

internal cooling medium

O: oil

K: insulating liquid with fire point > 300°C

L: insulating liquid with no measurable fire point

external cooling medium

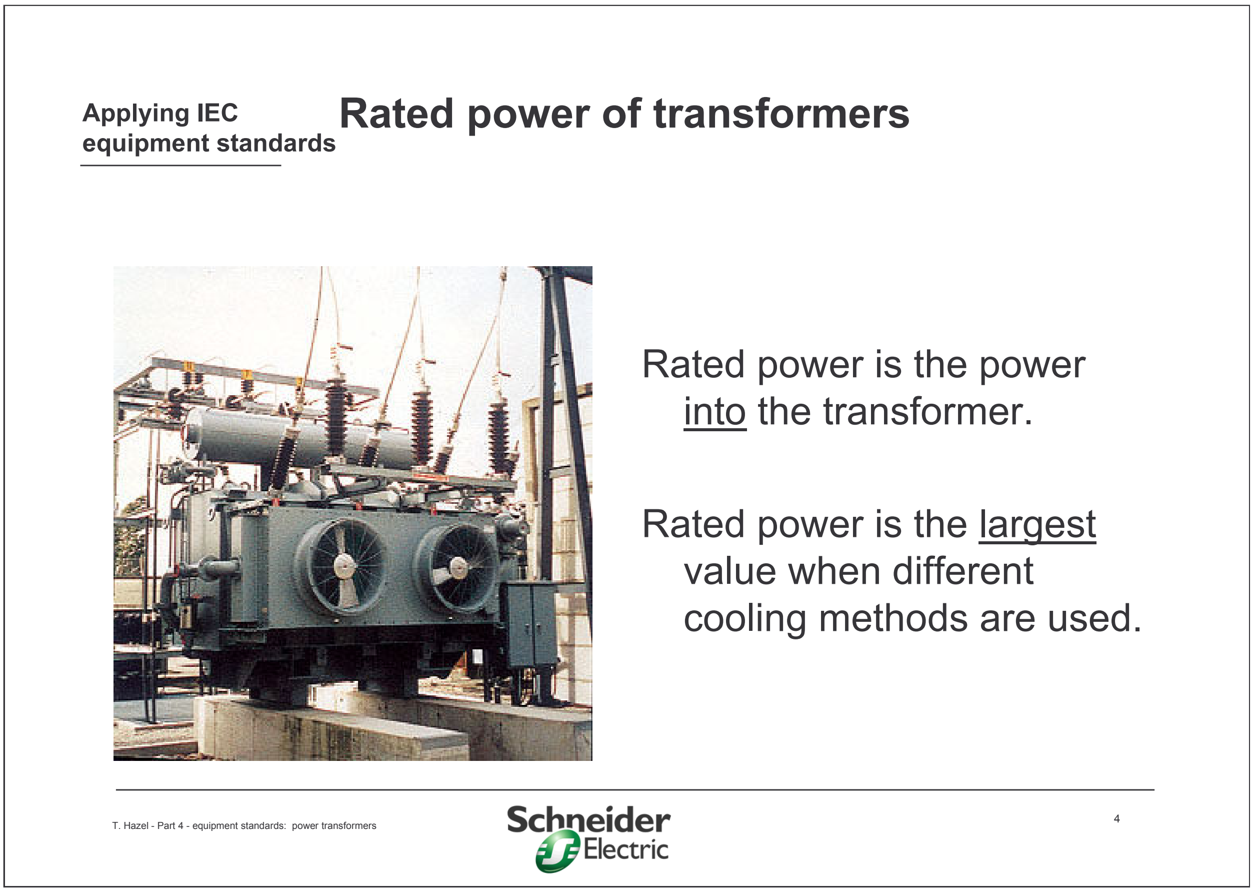
A: air

W: water

circulation mechanism

N: natural

F: forced



Applying IEC equipment standards

Rated power of transformers

Rated power is the power into the transformer.

Rated power is the largest value when different cooling methods are used.

apparent power

The IEC definition of rated apparent power can easily be misunderstood. This is illustrated in the following sections.

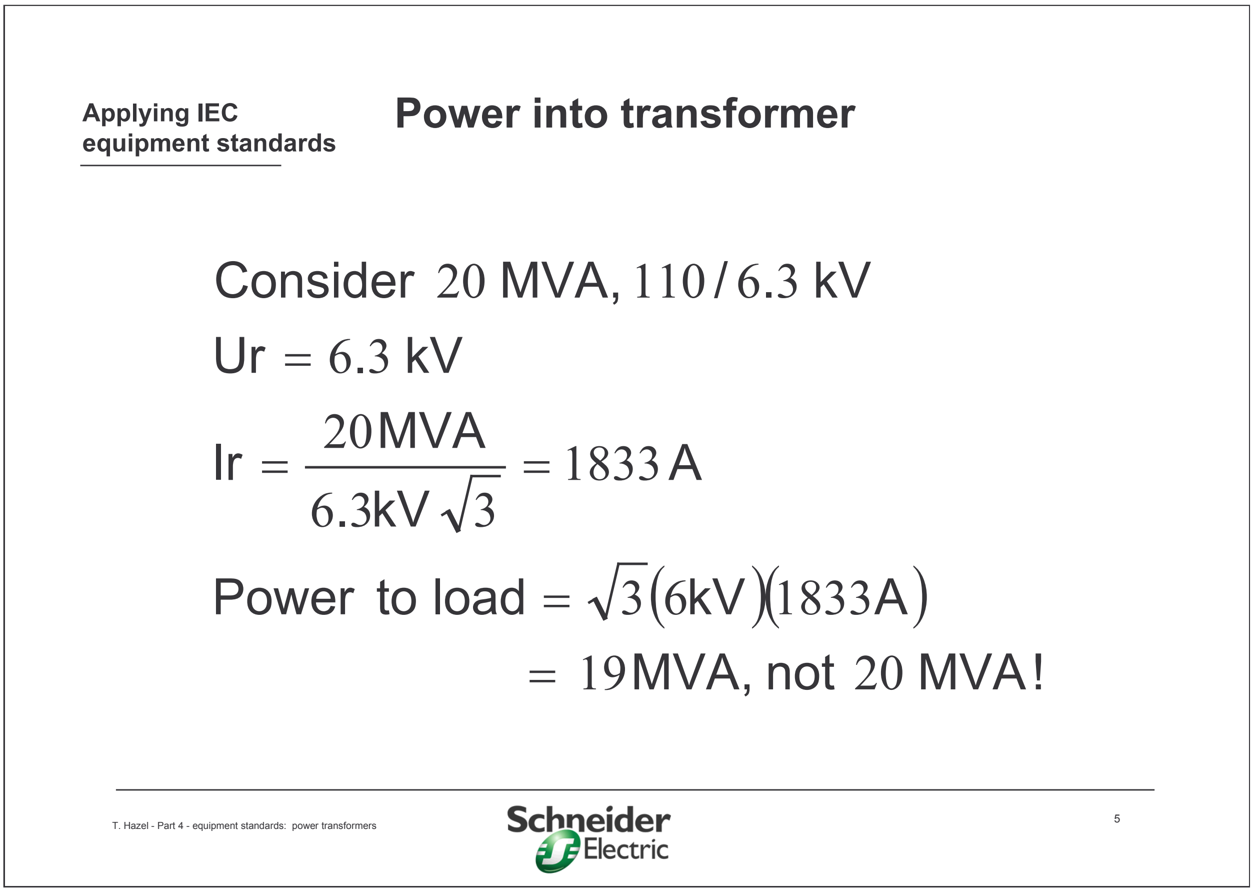
how rated power is defined

Rated power Sr is defined in sub-clause 4.1 of IEC60076-1 as the power **into** a transformer. The power available for the load is therefore generally slightly less than the rated power of the transformer.

rated power based on cooling method

Sub-clause 4.1 IEC60076-1 states that if different values of apparent power are assigned under different circumstances, for example with different methods of cooling; the **highest** of these values is the rated power. This is one of the main reasons for confusion.

NOTE: For better understanding of subsequent sections, rated power is defined based on the service conditions of sub-clause 1.2 of IEC60076-1 (altitude $\leq$ 1000m, ambient temperature $\leq$ 40°C), without exceeding the temperature rise defined in IEC60076-2.



Power into transformer

Consider 20 MVA, $110/6.3$ kV

$$Ur = 6.3 \text{ kV}$$

$$Ir = \frac{20\,\text{MVA}}{6.3\text{kV}\sqrt{3}} = 1833\,\text{A}$$

$$\text{Power to load} = \sqrt{3}(6\text{kV})(1833\text{A})$$

$$= 19\,\text{MVA, not } 20 \text{ MVA!}$$

Schneider Electric

underestimating the rated power required

The transformer was specified as:

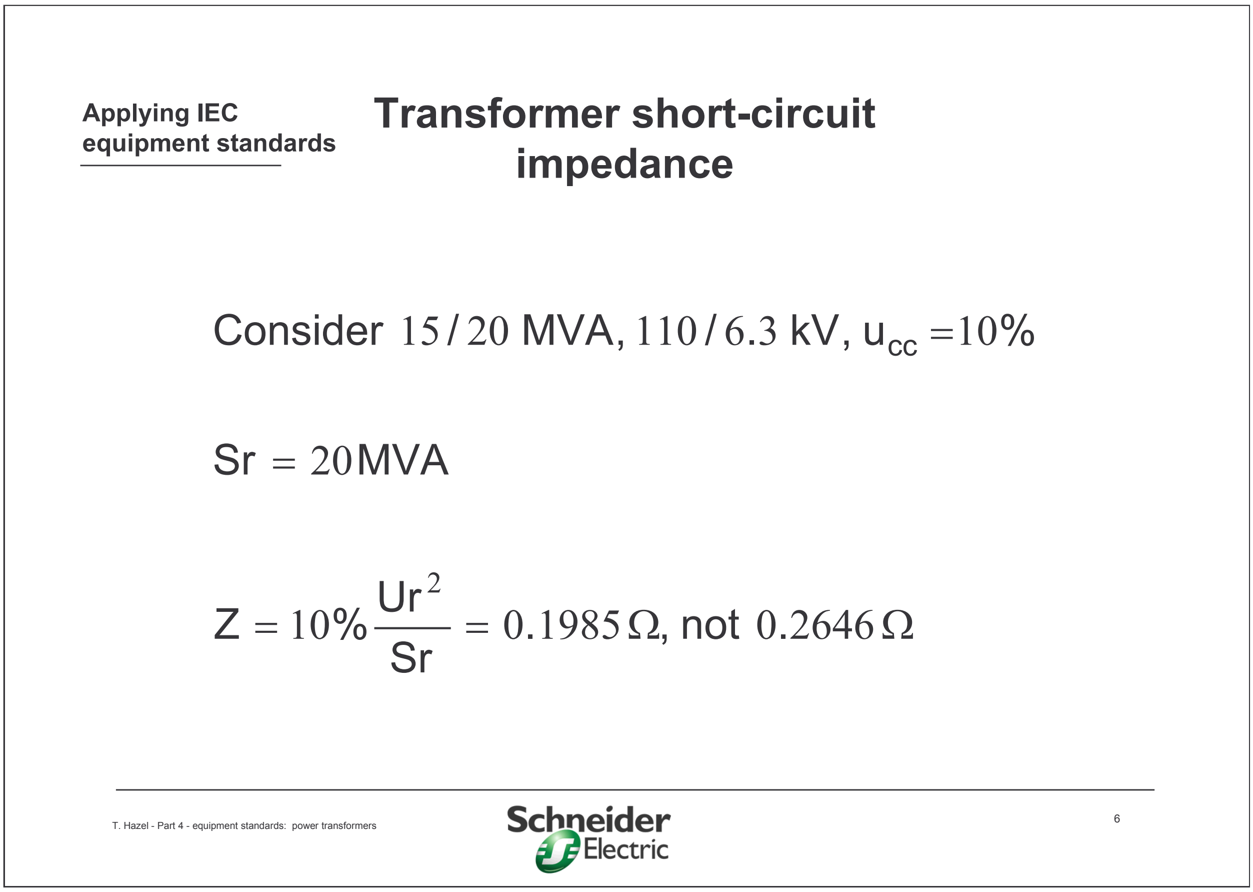
- ❑ 20 MVA transformer, 110kV/6.3kV
- ❑ Ur = 110kV on primary winding
- ❑ Ur = 6.3kV on secondary winding

where Ur is the rated voltage of a winding. By IEC definition rated voltages of all windings appear simultaneously at no-load when the voltage applied to one of them has its rated value (sub-clause 3.4.3 IEC60076-1)

The rated secondary current is $I_r = \frac{S_r}{U_r\sqrt{3}} = \frac{20\text{MVA}}{6.3\text{kV}\sqrt{3}} = 1833\text{A}$

If the voltage drop is about 5% in the transformer, the load voltage is 6kV and the power output is $\sqrt{3}(6\text{kV})(1833\text{A}) = 19\,\text{MVA}$

One client claimed that he had been cheated since he had specified and paid for a 20 MVA transformer which could only supply a load of 19 MVA at best. Although the IEC standard is very clear in its definition of rated power, this misunderstanding took much time and effort to clarify and the result was an unsatisfied customer.



Transformer short-circuit impedance

Consider $15/20$ MVA, $110/6.3$ kV, $u_{cc} = 10\%$

$$Sr = 20 \text{MVA}$$

$$Z = 10\% \frac{Ur^2}{Sr} = 0.1985\,\Omega, \text{ not } 0.2646\,\Omega$$

underestimating short-circuit current

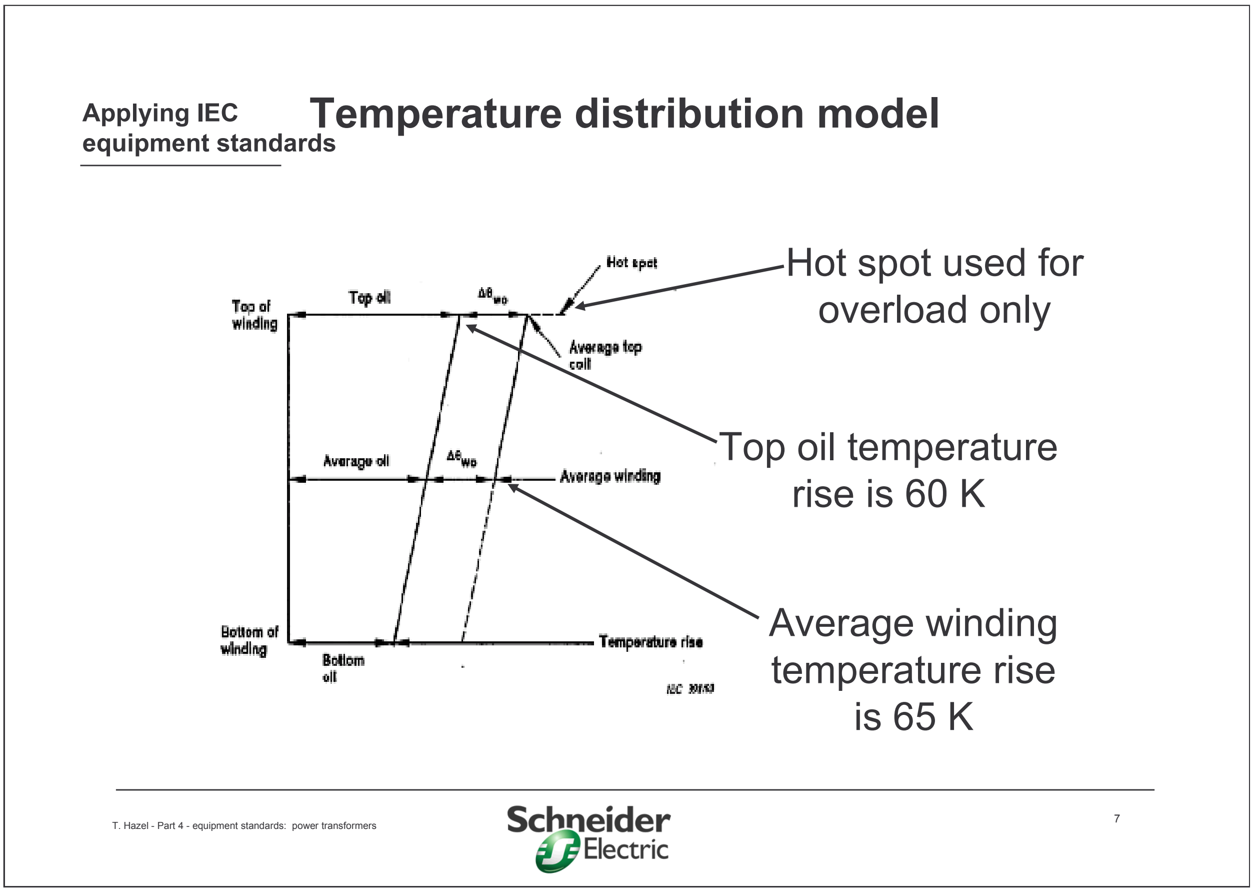
Consider the following transformer: 15/20 MVA ONAN/ONAF, 110/6.3kV, u_{cc} 10%

Sr is 20 MVA and the short-circuit impedance is

$$Z = 10\% \frac{U_r^2}{S_r} = 0.1985\,\Omega$$

not 0.2646Ω which would be found using 15 MVA..

This can lead to underestimating the short-circuit current if the value of apparent power corresponding to natural cooling is used. For 3-winding transformers the power used as a reference to calculate the short-circuit impedance for each winding should always be stated since this is very often confusing no matter what standards are used.



Applying IEC equipment standards

Temperature distribution model

Hot spot
Top of winding
Top oil
$\Delta\theta_{wo}$
Average top coil
Average oil
$\Delta\theta_{wo}$
Average winding
Bottom of winding
Bottom oil
Temperature rise
IEC 391/93

Hot spot used for overload only

Top oil temperature rise is 60 K

Average winding temperature rise is 65 K

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standard ambient conditions and materials

IEC60076 assumes that class A insulation and mineral oil are used. Class A insulation as per IEC60085 has a maximum hot spot temperature of 105°C.

Sub-clause 4.2 IEC60076-2 defines 2 temperatures for heat rise:

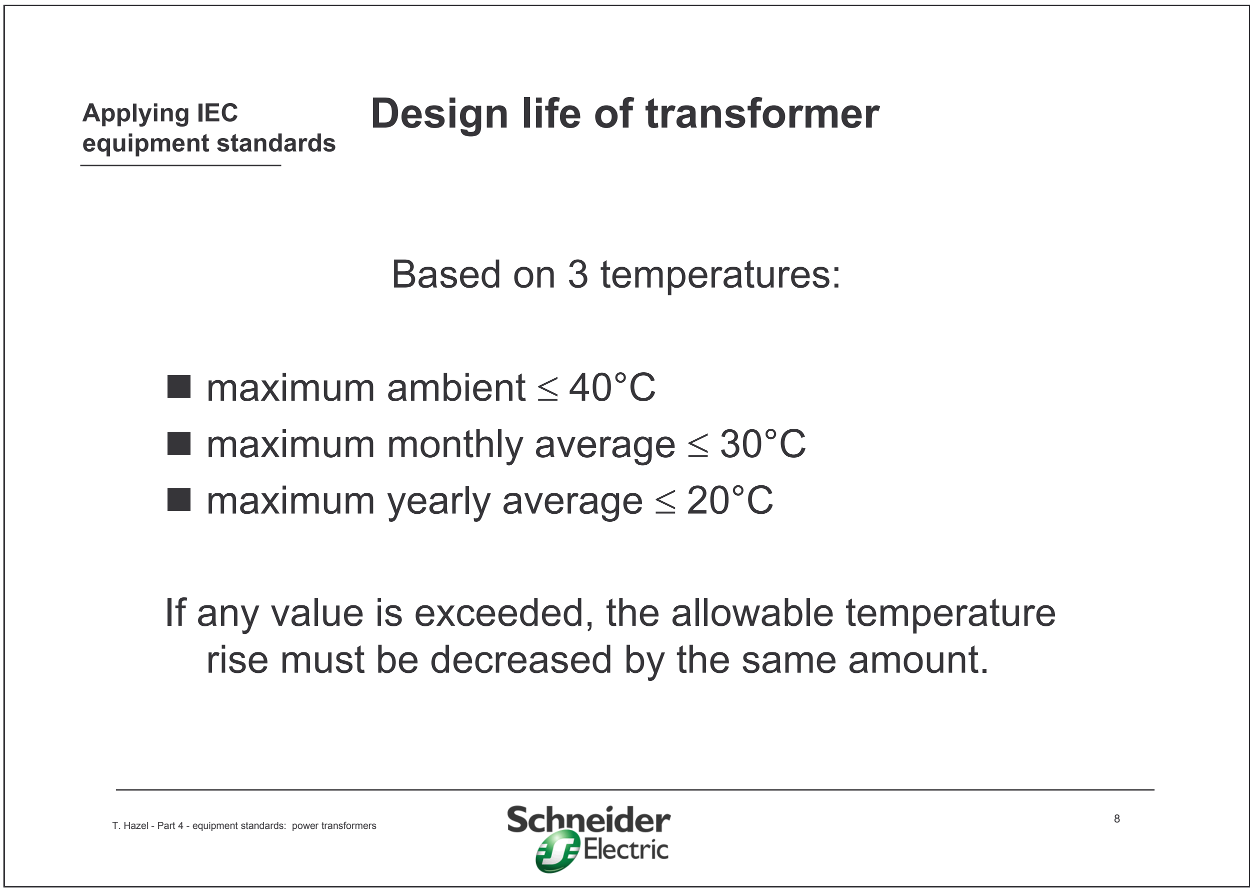
☐ 60K for top oil temperature rise

☐ 65K for average winding temperature rise (not the hot spot)

NOTE: Although 1K = 1°C, for temperature rise always use K. For actual temperatures use °C. Confusion often occurs when °C is used for temperature rise.

specifying other temperature rises

Confusion occurs when only one value of temperature rise is specified, or when 2 different sets of temperature rises are specified. These have no meaning in the IEC standards and therefore no testing to demonstrate compliance can be done. (Temperature rise for overload conditions will be discussed in a later chapter.)



Applying IEC equipment standards

Design life of transformer

Based on 3 temperatures:

- maximum ambient ≤ 40°C
- maximum monthly average ≤ 30°C
- maximum yearly average ≤ 20°C

If any value is exceeded, the allowable temperature rise must be decreased by the same amount.

standard ambient conditions as per IEC

Should no information be given in the technical specifications, IEC60076 assumes the following:

☐ The altitude where the transformer is installed is ≤ 1000 m.

☐ The standard temperatures given in sub-clause 4.3.1 of IEC60076-2 are:

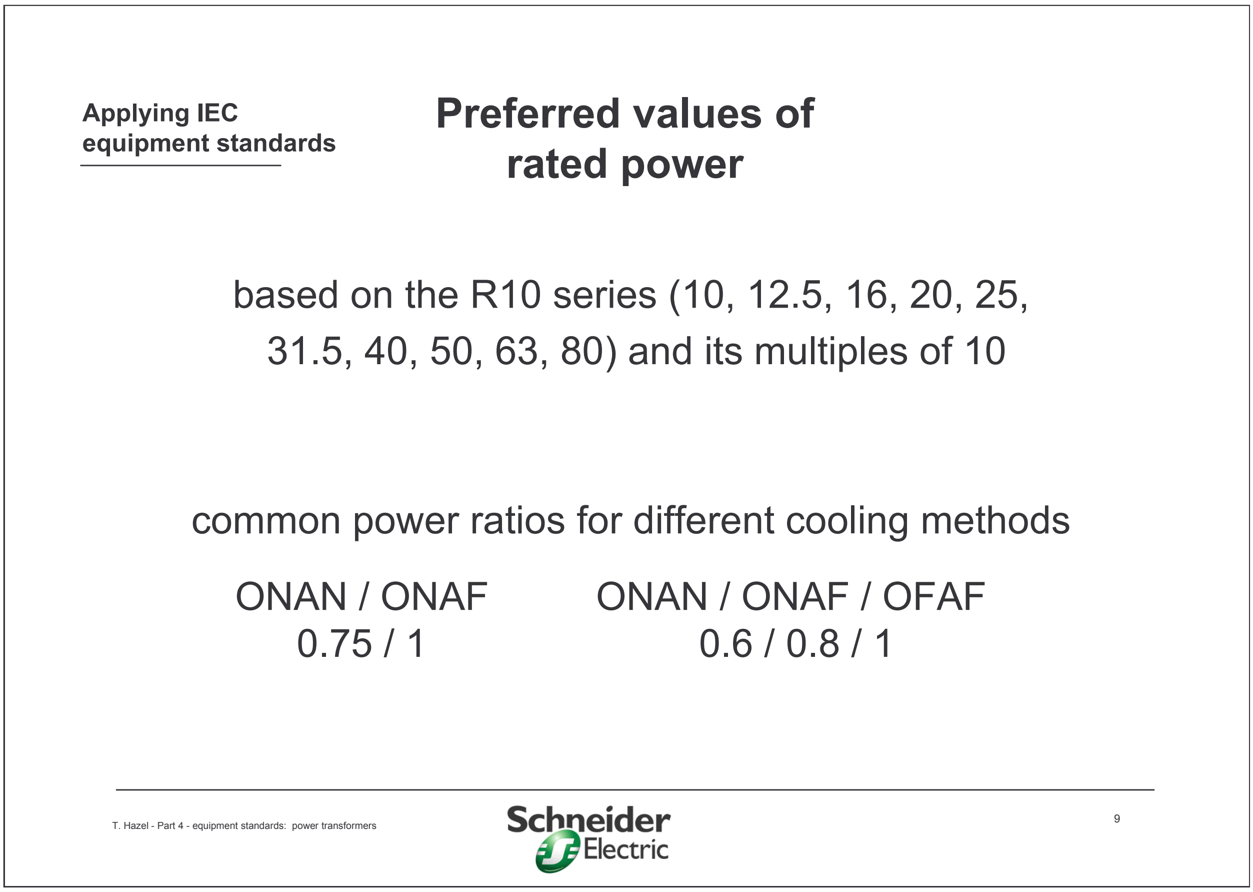
-maximum ambient temperature ≤ 40°C

-maximum monthly average temperature ≤ 30°C

-maximum yearly average temperature ≤ 20°C

-If water is used for cooling the temperature is ≤ 25°C.

The 30°C maximum monthly average temperature should not be confused with the 35°C maximum daily average temperature used in switchgear and controlgear standards.



Preferred values of rated power

based on the R10 series (10, 12.5, 16, 20, 25, 31.5, 40, 50, 63, 80) and its multiples of 10

common power ratios for different cooling methods

ONAN / ONAF	ONAN / ONAF / OFAF
0.75 / 1	0.6 / 0.8 / 1

Note that the highest value is equal to 1. Thus the ONAN rating is 75% of the ONAF rating. If 1 was assigned to the ONAN rating, then the ONAF rating would be 1.333 times the ONAN rating.

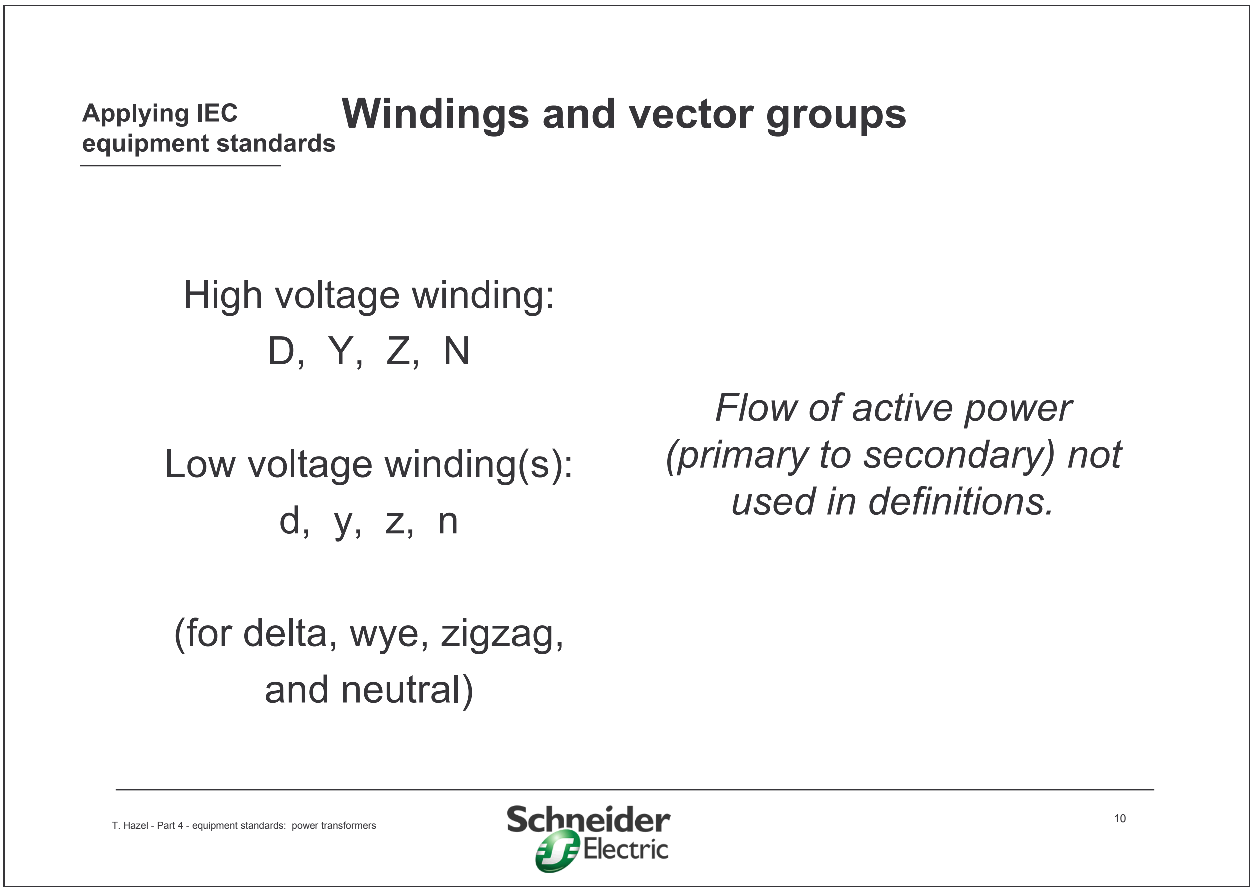
preferred values of apparent power

Sub-clause 4.3 IEC 60076-1 gives preferred values of rated power up to 10 MVA based on the ubiquitous R10 series (each value is approximately 25% more than the previous value) which is also used for rated current and rated short-circuit current.

The R10 values are 10, 12.5, 16, 20, 25, 31.5, 40, 50, 63, 80.

The preferred rated power values are these R10 values and their multiples of 10. The values are preferred but there is no obligation to use them.

The IEC standards do not give any preferred values for the ratio of the powers associated with different cooling methods. Common practice of manufacturers of IEC transformers is shown above.



Applying IEC equipment standards

Windings and vector groups

High voltage winding:
D, Y, Z, N

Low voltage winding(s):
d, y, z, n

(for delta, wye, zigzag,
and neutral)

Flow of active power (primary to secondary) not used in definitions.

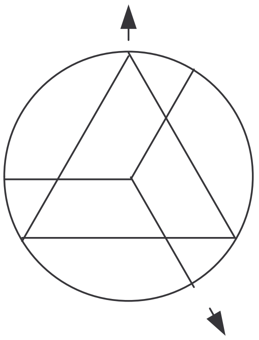
definition of windings and vector groups

IEC60076-1 gives the method to be used to define the connection of the windings and the related phase shifts. The IEC definitions are based on the rated voltages of the windings, not on the direction of active power flow. If incorrectly understood, this can lead to confusion especially when step-up transformers are used. Please refer to the single-line diagram in part 2 of the tutorial for examples.

primary and secondary windings

The majority of transformers receive active power from a source connected to the *primary* winding and deliver it to a load connected to the *secondary* winding. Some transformers are also used in applications where active power can flow in both directions through the transformer. The terms *primary* and *secondary* have no significance as to which winding has the higher rated voltage and therefore should not be used when specifying transformers.

Clock notation



HV winding phase
voltage at 0°

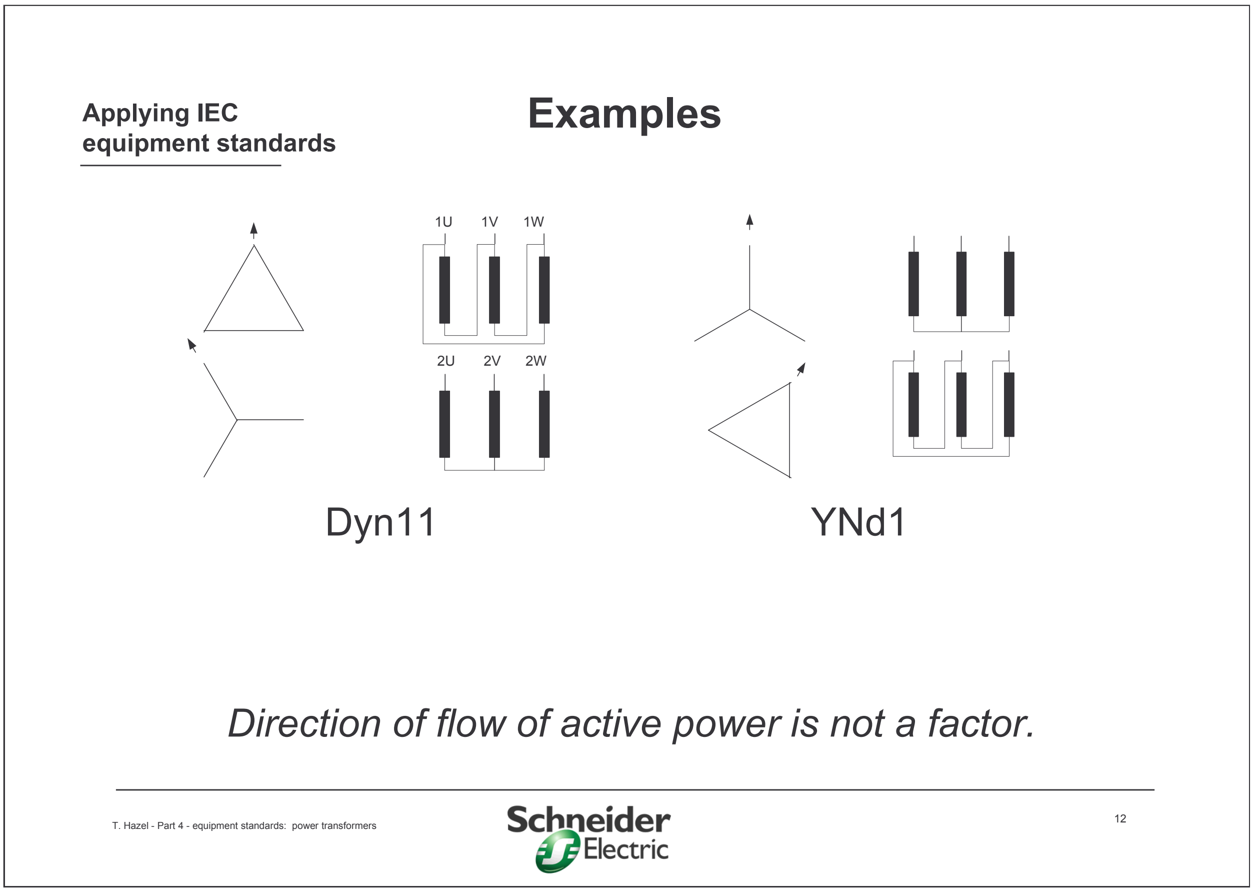
LV winding phase
voltage at 5 o’clock
lags HV by 5 x 30° = 150°

phase displacement symbols

The phase displacement is the angular difference between the phasors representing the voltages between the neutral point (real or imaginary) and corresponding terminals of 2 windings. The displacement is indicated using the clock notation, that is the hour indicated by the LV or intermediate winding phasor when the HV winding phasor is at 12 o'clock (rising numbers indicated increasing phase lag). Each hour corresponds to 30°.

In the example above, the HV winding is delta connected and the phase voltage points to 12 o'clock. The LV winding is wye connected and the corresponding phase voltage points to 5 o'clock giving Dy5.

Low-voltage winding always lags the high-voltage winding.



Applying IEC equipment standards

Examples

Dyn11

YNd1

Direction of flow of active power is not a factor.

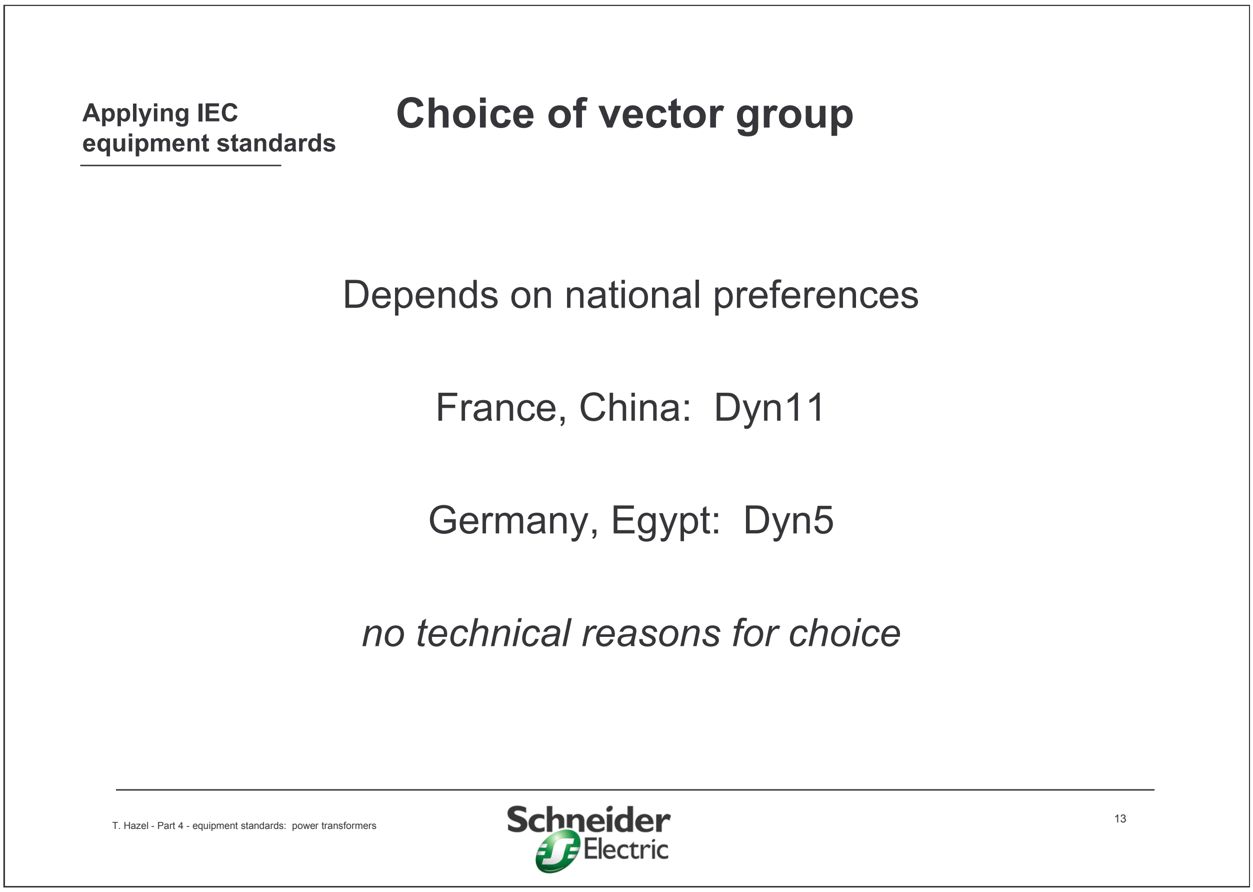
example 1: Dyn11

Transformer with rated voltages 110kV delta connected, and 6.9kV star connected with the neutral brought out, and the voltage of phase A of the LV winding lagging the voltage of phase A of the HV winding by 330°. This is a step-down transformer supplying loads at a rated system voltage of 6.6kV.

example 2: YNd1

Transformer with rated voltages 115kV star connected with the neutral brought out, and 33kV delta connected, lagging the HV winding phasor by 30°.

This is a step-up transformer with active power flowing into the 33kV winding and out of the 115kV winding, 115kV being the no-load voltage corresponding to a rated system voltage of 110kV as defined in IEC60038.



Applying IEC equipment standards

Choice of vector group

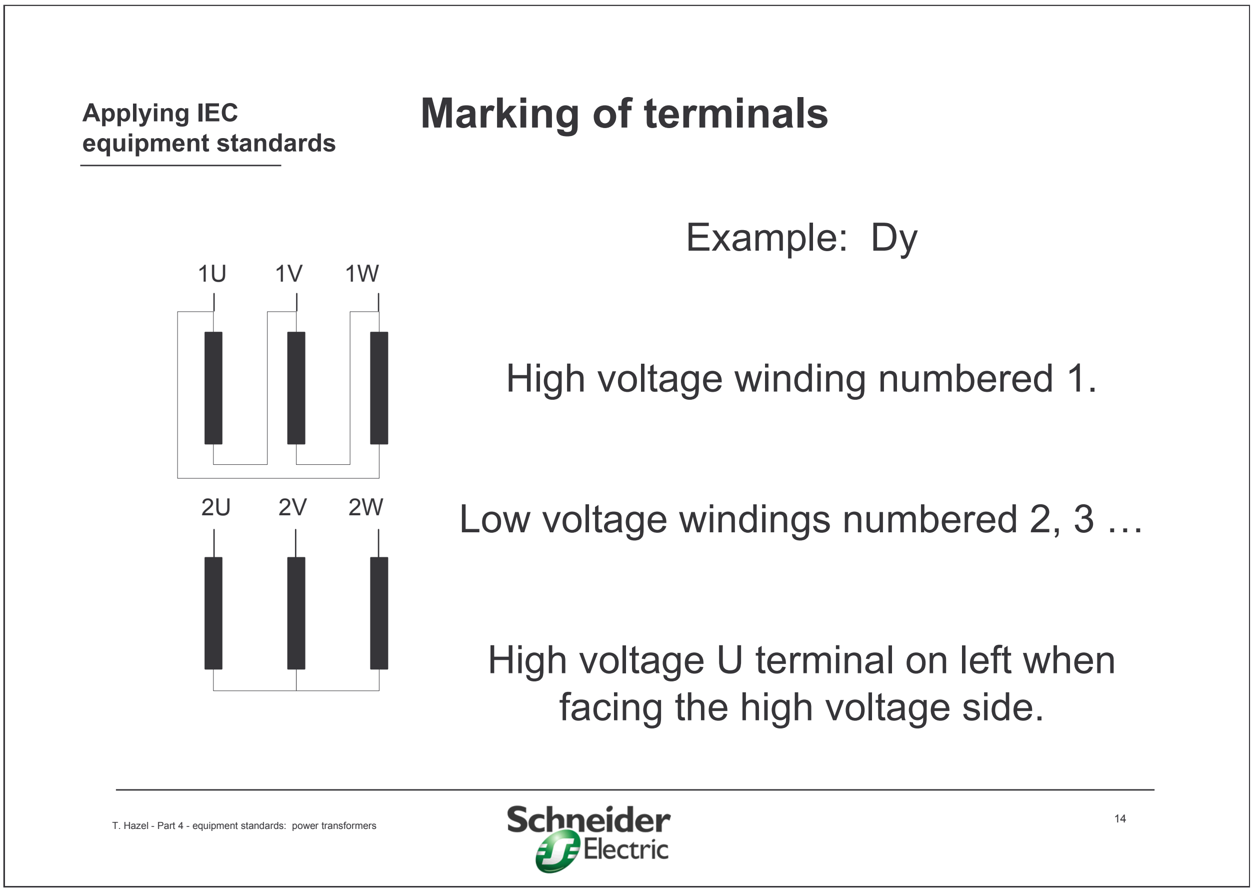
Depends on national preferences

France, China: Dyn11

Germany, Egypt: Dyn5

no technical reasons for choice

There are many winding connections and phase displacements possible. Annex D IEC60076-1 shows *common connections*, *additional connections*, *auto-transformer connections*, and a *three-phase bank connection* (see the appendix to this part of the tutorial). It is important to realize that the IEC standards do not recommend the use of any particular phase displacements. The phase displacements used are based on standard national practice in the country where the transformer will be installed. For example in France and China a phase displacement of 330° (Dyn11) is very common, whereas a phase displacement of 150° (Dyn5) is very common in Germany and Egypt.



Applying IEC equipment standards

Marking of terminals

Example: Dy

High voltage winding numbered 1.

Low voltage windings numbered 2, 3 …

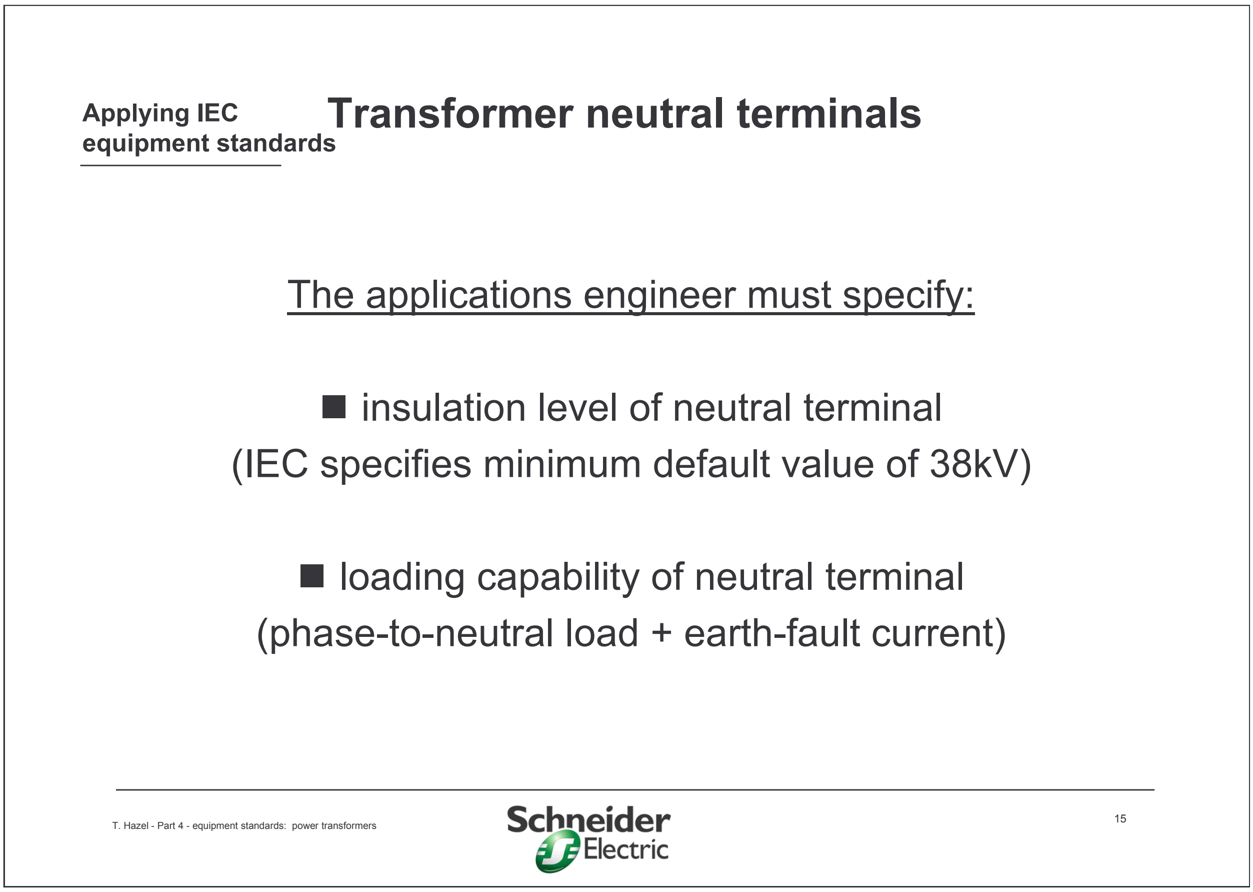
High voltage U terminal on left when facing the high voltage side.

marking and location of terminals

The guidelines for markings on the terminals of power transformers are given in IEC60616. The following points are important:

- The line terminals of the windings are marked U, V, W. The neutral terminal is marked N. Capital letters are used for all windings, not just the high-voltage winding.
- The various windings are denoted by reference numbers preceding the letters, with the high-voltage winding having the reference number 1. The other windings have 2, 3, 4... in descending sequence of their rated voltage.
- There is no reference to *primary* and *secondary* windings based on the flow of active power.

The marking for a Dy connection is shown above.



Applying IEC equipment standards

Transformer neutral terminals

The applications engineer must specify:

- insulation level of neutral terminal
(IEC specifies minimum default value of 38kV)

- loading capability of neutral terminal
(phase-to-neutral load + earth-fault current)

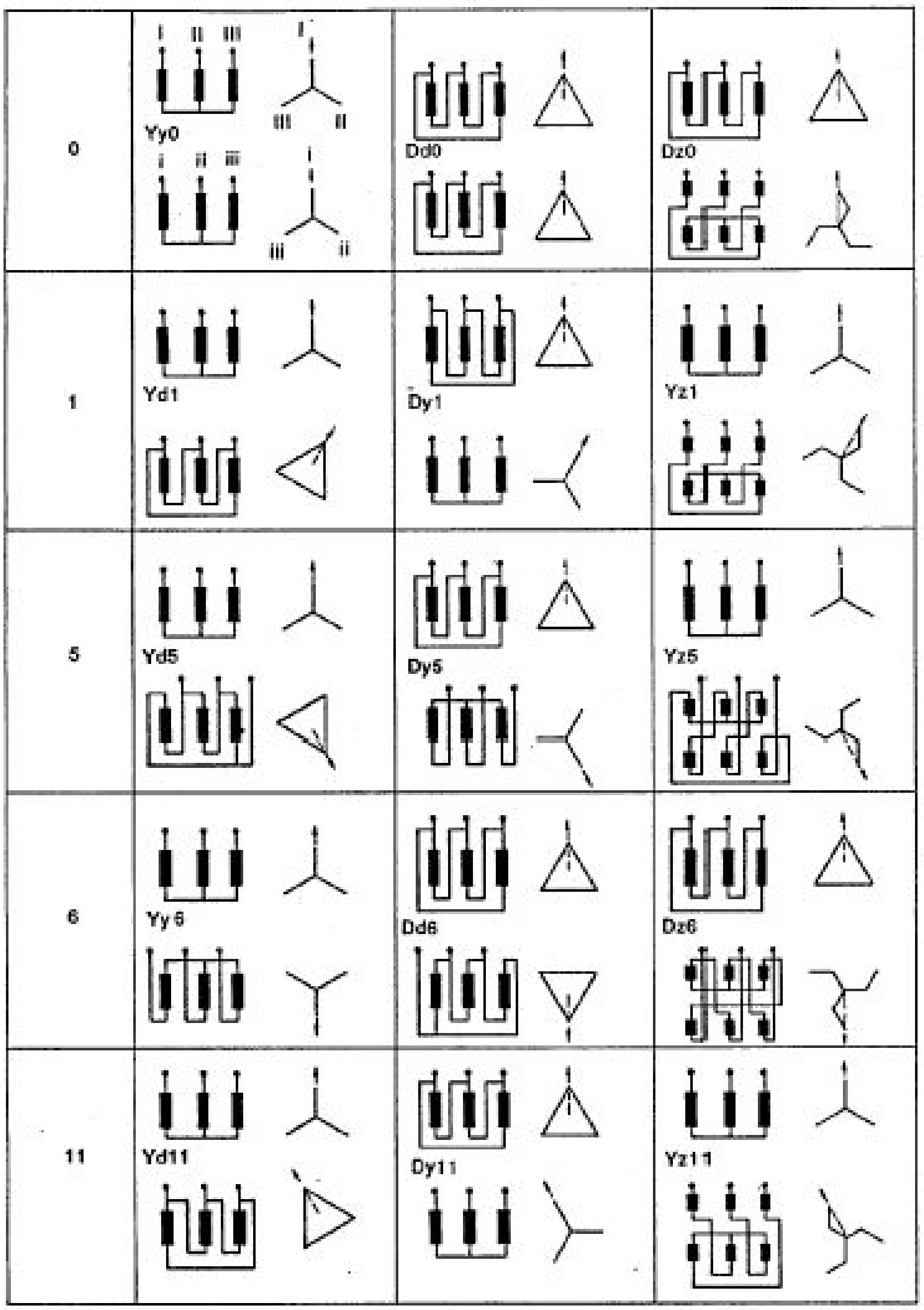
neutral terminals

Special care must be taken with neutral terminals. The overvoltages that the neutral terminal is subject to depends on how it is connected to earth. The applications engineer is responsible for determining this based on the overall electrical distribution system and therefore he must specify the requirements (this is stated in sub-clause 5.5.3 IEC60076-3). Reliance on the manufacturer to determine the correct neutral terminal insulation could lead to an incorrect design since he could assume a direct connection to earth and simply provide a terminal rated for 38kV as per sub-clause 5.5.2 IEC60076-3. Special care for the loading capability of the neutral is required as well as per sub-clause 8.1 IEC60076-1. The neutral must be designed for the load between phase and neutral in addition to the earth-fault current, both of which depend on the application.

Transformer connections 1/3

Three-phase transformer connections

Common connectio


0
I II III
I III II
Yy0
i ii iii
i iii ii
Dd0
Dz0
1
Yd1
Dy1
Yz1
5
Yd5
Dy5
Yz5
6
Yy6
Dd6
Dz6
11
Yd11
Dy11
Yz11

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